

# $\pi^0$ Transverse Single Spin Asymmetries at High $x_F$ in $p^\uparrow + p$ collisions with the PHENIX detector

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**Abstract.** Using the Muon Piston Calorimeter (MPC), which covers  $3.1 < |\eta| < 3.7$ , the PHENIX detector at RHIC has measured large transverse single spin asymmetries  $A_N$  for single inclusive high  $x_F$   $\pi^0$ 's in transversely polarized proton collisions. We will present the measured asymmetries from two different collision energies, one at  $\sqrt{s} = 200$  GeV with an integrated luminosity of  $\sim 5.2 \text{ pb}^{-1}$  and the other at  $\sqrt{s} = 62$  GeV with  $\sim 20 \text{ nb}^{-1}$ . The relatively large values for the asymmetries make these measurements interesting for decoupling the various effects which have been proposed to generate transverse asymmetries in  $p^\uparrow + p$  collisions, and may eventually lead to a greater understanding of the internal angular momentum structure of the proton.

## 1. Introduction

Measurements of double longitudinal cross-section asymmetries at the Relativistic Heavy Ion Collider (RHIC) suggest that the contribution to the proton's spin from gluon spin  $\Delta G$  is perhaps not very large, and might be much less than the remaining 75% of the proton's spin that is unknown [1, 2]. Future measurements at RHIC will continue to probe for the possibility that the gluon spin is sizable in the proton at low momentum fraction  $x$ , but if the gluon spin is indeed too small to make up the rest of the proton's spin, any remaining contribution likely comes from quark or gluon orbital angular momentum (OAM). Since the OAM is related to the three-dimensional structure of the proton, investigation of effects which probe OAM has become a very active area of research in recent years.

Currently, there are two main experimental approaches to measure effects from the three-dimensional structure of the proton. One is a measurement of generalized parton distributions through deeply virtual compton scattering reactions in  $e + p^\uparrow$  collisions. The other is to measure transverse momentum dependent distributions (TMDs) via asymmetries in semi-inclusive deep inelastic scattering of  $e + p^\uparrow$  collisions or in transversely polarized hadron collisions. As the world's only polarized proton collider, RHIC is the only place to study the latter at collider energies, and indeed, large left-right single spin transverse asymmetries in inclusive hadron production at high Feynman  $x_F = 2x_L/\sqrt{s}$  from polarized proton collisions have been published by the STAR and Brahm's collaborations [3, 4, 5]. Several theoretical proposals to explain these single spin asymmetries have been proposed, such as the Sivers mechanism [6], the Collins mechanism [7], or higher twist effects [8]. It is also possible that all of the above mechanisms are valid, and that the resultant effect is an admixture of all three. These proposals extend the

standard leading order, collinear, and factorized perturbative QCD description by introducing a transverse momentum dependence to the parton and fragmentation distributions.

While transverse spin asymmetries of hadron production have been observed already two decades ago, measurement of these asymmetries at the collider energies provided by RHIC might be advantageous since this is a regime where a description in terms of perturbative QCD has been shown to be valid for the unpolarized case. This hope would be especially true for those prescriptions which require a perturbative expansion, such as the higher twist calculations. Recent work which shows that factorization is violated for hadronic processes involving transverse momentum dependent distributions complicates this view [9]. However, this also provides an opportunity since it might be possible to calculate the factorization breaking effects for each process.

In the 2006 RHIC run, a new  $PbWO_4$  based electromagnetic calorimeter, the Muon Piston Calorimeter (MPC) [10], was proposed and installed at forward rapidity covering  $3.1 < \eta < 3.7$  on one side of the PHENIX experiment, about 220 cm from the interaction point. Additional calorimetry covering the opposing side, at  $3.1 < \eta < 3.9$ , was installed for the 2007 run. These proceedings present measurements using the MPC of the single inclusive  $\pi^0$  asymmetries at  $\sqrt{s} = 62.4$  GeV and cluster asymmetries dominated by  $\pi^0$ 's at  $\sqrt{s} = 200$  GeV. The dataset comprises an integrated luminosity of approximately  $20 \text{ nb}^{-1}$  of  $p^\uparrow + p$  at  $\sqrt{s} = 62$  GeV taken during the 2006 run at RHIC, and approximately  $2.7 \text{ pb}^{-1}$  at a  $\sqrt{s} = 200$  GeV taken during the 2008 run. The average beam polarizations were about 50% and 46%, respectively. This data provides strong tests of the theories by probing the collision energy dependence, the isospin dependence, and the  $p_T$  dependence at very high  $p_T$  of the observed  $\pi^0$  asymmetries.

## 2. Data Analysis and Results

The MPC  $PbWO_4$  crystals are  $2.2 \times 2.2 \times 18 \text{ cm}^3$  and have a Moliere radius of 2 cm. Including the wrapping that is needed for light isolation, the typical crystal spacing is 2.26 cm. With these parameters, at energies above  $\sim 20$  GeV the two photons from the  $\pi^0$  decay merge into a single cluster which cannot be easily separated. The composition of these clusters have been studied with the PYTHIA monte carlo, and according to PYTHIA, they are dominantly from  $\pi^0$ 's, with another 15% coming mostly from  $\eta$  mesons and direct photons. For the 62.4 GeV collision energy this means that one can reach up to  $x_F \approx 0.6$  before the decay photons from the  $\pi^0$ 's fully merge. The higher energies in 200 GeV collisions mean that the decay photons are merged into a single cluster above  $x_F \approx 0.2$ , so for the 200 GeV data set we measure the cluster asymmetry in the MPC in order to reach higher  $x_F$ . There remains an admixture of 15%  $\eta$ 's and direct photons which should be possible to self-consistently account for in any theory.

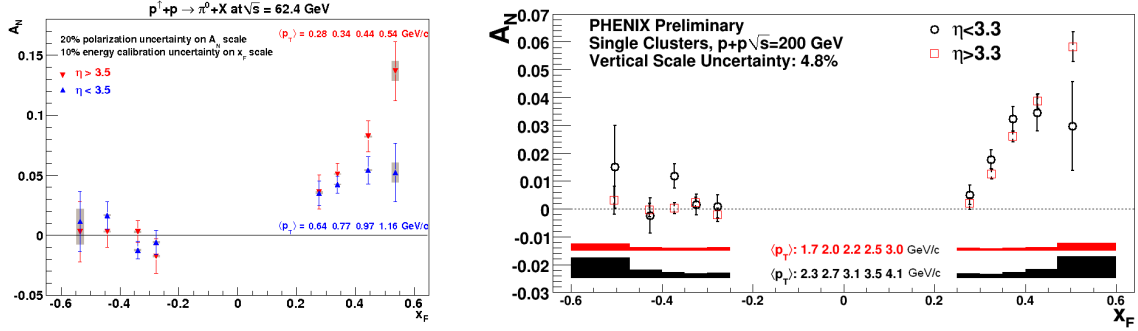
The gains as well as the overall energy scale for each crystal were determined and cross-checked by a combination of the minimum ionizing peak, the inverse slope of the spectrum in each crystal, and the  $\pi^0$  and  $\eta$  meson peaks. We count the left-right asymmetry  $A_N$  in the production of  $\pi^0$ 's relative to the spin direction of the proton, where  $A_N$  is defined by

$$A_N = \frac{1}{P} \frac{\sigma^\uparrow - \sigma^\downarrow}{\sigma^\uparrow + \sigma^\downarrow} \quad (1)$$

where  $P$  is the beam polarization. The asymmetries are determined by two methods. One is to measure the geometric mean  $\sigma^\uparrow = \sqrt{N_L^\uparrow N_R^\downarrow}$  and  $\sigma^\downarrow = \sqrt{N_L^\downarrow N_R^\uparrow}$ , where  $N_L^\uparrow$  is the count of  $\pi^0$ 's produced to the left of the proton bunches that are polarized upward, and  $N_R^\downarrow$  is the count to the right of the downward polarized bunches. The other technique is to measure the pure polarization asymmetries,  $\epsilon_P = (N^\uparrow - N^\downarrow)/(N^\uparrow + N^\downarrow)$ . The above two distributions are binned in azimuth, and fit to  $A_N \cos(\phi + \phi_0)$  and  $R + \epsilon_N \cos(\phi + \phi_0)$ , respectively, where  $\phi_0$  accounts for a possible deviation of the proton polarization from vertical,  $R$  accounts for the relative

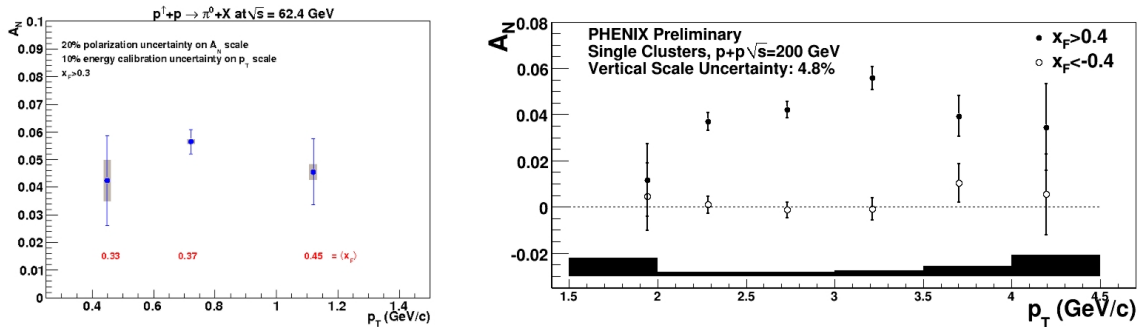
luminosity between the two different polarization states of the proton, and  $\epsilon_N = PA_N$ . Both techniques agree well with each other.

In figure 1 the single spin asymmetry  $A_N$  is plotted as a function of  $x_F$  for  $\sqrt{s} = 62$  GeV and  $\sqrt{s} = 200$  GeV, respectively. In both cases, one sees asymmetries that are consistent with zero in the negative  $x_F$  region, which is in the direction of the unpolarized proton. For positive  $x_F$  there are sizable asymmetries which generally grow with increasing  $x_F$ , with a flattening out of the asymmetry when one selects  $\pi^0$ 's at more forward pseudorapidity.



**Figure 1.** The  $x_F$  dependence of the neutral pion analyzing power  $A_N$  at  $\sqrt{s} = 62$  GeV (left) and for clusters at  $\sqrt{s} = 200$  GeV (right) in the MPC. The grey, red, and black bands show the magnitude of the systematic errors.

The  $p_T$  dependence of the asymmetry is shown in figure 2. There is a kinematic limit of  $p_T \sim 3$  GeV/c for the lower collision energy of 62.4 GeV. With the short run, statistics begins to run out at a  $p_T$  of  $\sim 1.5$  GeV/c. For the 200 GeV run, the asymmetry rises to a maximum at about 3.2 GeV/c, with perhaps a drop at 4.5 GeV/c. The behavior at higher  $p_T$  is of great interest since the expectation is that when a perturbative expansion is applicable, the asymmetry should fall with higher  $p_T$ . Previous data had not extended out far enough in  $p_T$  to see this drop [4], so this data might provide the first hints of the expected falling behavior at high  $p_T$ .



**Figure 2.** The  $p_T$  dependence of the neutral pion analyzing power  $A_N$  at  $\sqrt{s} = 62$  GeV (left) and  $\sqrt{s} = 200$  GeV (right), with the systematic errors shown in the grey and black bands.

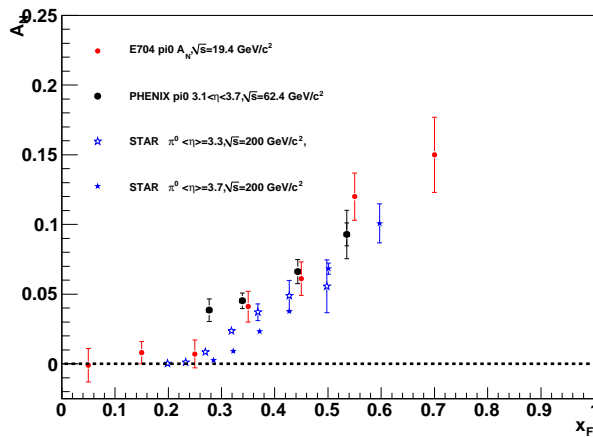
### 3. Discussion

The low  $p_T$  that is reached in the 62.4 GeV collision data does bring into question the ability to interpret the results from a partonic and perturbative treatment of the data. This question can

be explored further by comparing the production cross-section to the NLO pQCD prediction, and it has been shown that the pion production cross-sections are well described in the forward region at  $\sqrt{s} = 200$  GeV [3] but not at the fixed target energies of 19.4 GeV. However, if one plots the  $A_N^{\pi^0}(x_F)$  from fixed target to collider energies, as shown in figure 3, there is a scaling with  $x_F$  which seems only weakly dependent on the collision energy. At forward rapidity  $x_F$  roughly approximates the momentum fraction  $x_1$  of the forward going proton since

$$x_F \equiv 2p_L/\sqrt{s} \approx 2\langle z \rangle p_{jet}/\sqrt{s} \approx \langle z \rangle x_1 \quad (2)$$

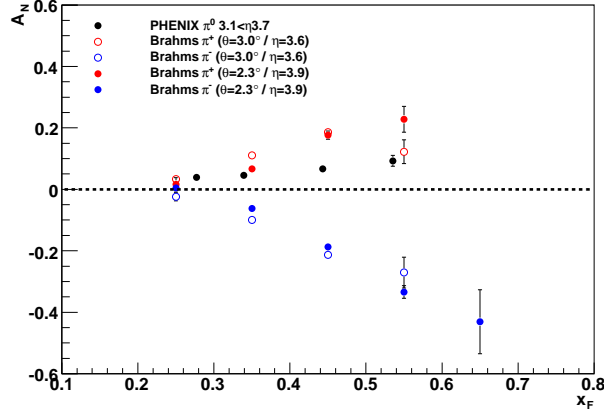
where  $\langle z \rangle$  is the mean momentum fraction of the hadron from the jet fragmentation. This was determined to be approximately 0.7 from our PYTHIA studies. This scaling with  $x_F$  provides a hint that the source of the asymmetries might come from the same source for all collision energies.



**Figure 3.** The  $A_N(x_F)$  dependence of  $\pi^0$ 's from  $p^\dagger + p$  collisions at  $\sqrt{s} = 19.4$ , 62.4, and 200 GeV [11, 4].

The dependence on isospin is another interesting aspect of these asymmetries. In figure 4, the asymmetry at 62.4 GeV is plotted for  $\pi^+$ ,  $\pi^0$ , and  $\pi^-$ . As an illustration of the utility of this data, we can check the hypothesis that the asymmetries come only from the Collins mechanism. In PYTHIA, one finds that the  $\pi^+$  comes mainly from the favored fragmentation of u quarks. The  $\pi^-$  is produced from an approximately equal mix of u and d quarks, and therefore has a sizable contribution from disfavored fragmentation. The  $\pi^0$  comes from 25% d and 75% u quarks. Extractions of the Collins from Belle indicate that the disfavored Collins fragmentation function is large and negative, which would qualitatively explain why  $|A_N^{\pi^-}| > A_N^{\pi^+}$ , assuming that transversity is not too different between the u and d quarks. Quantitative calculations of  $A_N$  from the Collins mechanism have been performed by various authors, with one group predicting only small asymmetries and the other group predicting the possibility of asymmetries comparable to what has been measured [12, 13], so the situation is uncertain.

In the last few years, a program to use a global fit of SIDIS data from the Hermes and Compass collaborations, based on an extraction of the Collins fragmentation function from measurements of the azimuthal fragmentation function in Belle, have yielded a measurement of the transversity distribution in the proton [14, 15, 16, 17]. It would be interesting to try this same program on the RHIC data, but before that can be reliably done, the  $\pi^0$  Collins fragmentation function must be measured at Belle, the contributions from Sivers and higher



**Figure 4.** The isospin dependence of the analyzing power  $A_N^{\pi^0}$  vs.  $x_F$  at  $\sqrt{s} = 62.4$  GeV from the PHENIX ( $\pi^0$ ) and BRAHMS ( $\pi^\pm$ ) [5] experiments.

twist effects must be determined, and the factorization breaking effects mentioned earlier must be calculated for the Collins mechanism. There is hope that this can be done, and would go a long way toward our understanding of how to relate transverse momentum dependent effects in very different processes such as  $e + e$ ,  $e + p^\uparrow$ , and  $p^\uparrow + p$ .

#### 4. Conclusion

PHENIX has measured the left-right single spin transverse asymmetry of single inclusive  $\pi^0$ 's covering high  $x_F$  up to 0.6 at two different collision energies. These measurements provide additional crucial information on the  $x_F$ ,  $p_T$ ,  $\sqrt{s}$ , and isospin dependence of these asymmetries. They may help to understand and possibly separate the possible causes of the large single spin asymmetries in hadron production from transversely polarized proton collisions, with the hope that the measurement of these TMD's might contribute to one day elucidating the three-dimensional structure of the proton.

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